PNNL-16159

D.O.E./GMIC/National Lab
G+ Project Final Letter Report

Project Title: Millimeter Wave diagnostics for Glass fiber drawing
Field of Use: Multifilamentary fiber drawing
Start Date: __05_/__01_/__03_ End-Date: __04/_30_/_04
Total cost: $25,000

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Note:

Since the completion of the project, Dr. Phillip Sanger and Dr. James A. Leonard have left the CSU. Dr. S. K. Sundaram has stayed in touch with them. He is also coordinating this report with Dr. S. Rekhson at CSU.

Abstract

The measurement of bushing temperatures and glass level inside the bushing are key glass fiber drawing process variables. However measuring the complete temperature profile on the bushing is not possible because the glass fibers themselves obstruct the line of sight. Millimeter waves (MMWs) however do not see the fibers due to their small diameter (5-10 microns) and offer a unique sensor approach not presently available in the industry. Moreover, MMWs offer the potential for the measurement of glass head pressure and glass viscosity, two other key variables to the glass fiber drawing process. The research project completed focused on setting up a MMW system at CSU on the 400 tip bushing and demonstrating the effectiveness of that technique in obtaining a clear temperature profile of the bushing. The team not only accomplished the goal of the project but also showed that MMW technology could also be used to detect fiber breakage. This letter report summarizes the technical work completed under this project during this period.

Relevance to roadmap:

Temperature profile in the bushing has been identified as a key parameter affecting breakage which directly impacts production efficiency (Roadmap goal #1). The development of sensors and controls that improve glass production efficiency has been clearly identified as an action step in the roadmap. Furthermore improved efficiency reduces process energy (#3), reduces glass scrap (#2), and reduces environmental emissions (#4).

Introduction:

On-line monitoring of glass melt processing can be realized through the use of millimeter-wave (MMW) technologies. Electromagnetic radiation in the 10 – 0.3 mm (30 – 1000 GHz) range of the spectrum is ideally suited for remote measurements in harsh, optically unclean and unstable processing environments. Millimeter waves are long enough to penetrate optical/infrared obscured viewing paths through dust, smoke, and debris, but short enough to provide spatially resolved point measurements for profile information. Another important advantage is the ability to fabricate efficient MMW melter viewing components from refractory materials. The same ceramics and alloys from which the melter/furnace is constructed could be used to fabricate MMW waveguide/mirror components that go into the melter for long life survivability. Therefore, ***we chose the MMW technology for our demonstration***.

Background:

Extensive laboratory work has established the basic configuration of a millimeter-wave sensor for multiple parameter measurements of the molten glass pool in a melter/furnace as shown in Figure 1. The basic building blocks are the millimeter-wave heterodyne receiver, a beamsplitter in the receiver field-of-view, a waveguide/optics transmission line to the melt pool, a window to seal the waveguide, and a thermal return reflection (TRR) mirror aligned with the split signal from the beamsplitter. Millimeter-wave signals are both received from, and transmitted to the molten glass. With this configuration, and slight modifications, it is possible to monitor all the melt pool parameters listed in Table 1 using only a single access point into the melter. The

physical melt pool effect that is being exploited in the millimeter-wave range to obtain the measured parameter is listed in the second column. More details of the hardware and measurement basis are given in references [1, 2]. It should be noted that Table 1 is not comprehensive. It shows only the parameter measurements that have been demonstrated so far by the MMW technology. Additional melt pool parameter measurement capability for liquidus, redox, noble metals, plenum temperature, and others are being developed.

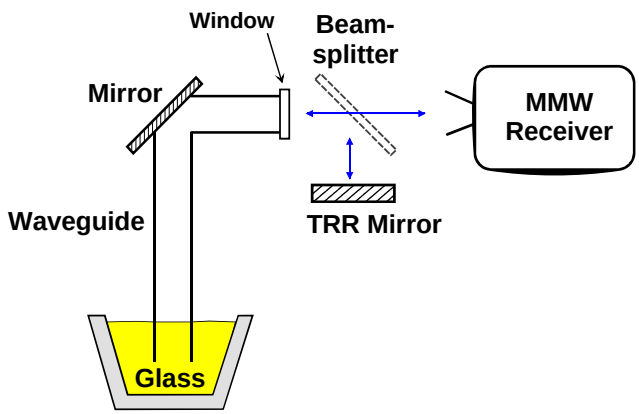


Figure 1. Basic millimeter-wave sensor configuration

Table 1. MMW Measurements

Parameter	Measured Effect
Temperature (T)	Thermal emission
Emissivity (ε)	Reflection amplitude
Density (ρ)	Reflection phase
Viscosity (η)	Reflection phase rate
Foaming	Surface acceleration/emissivity
Salt Layer	Emissivity/turbulence

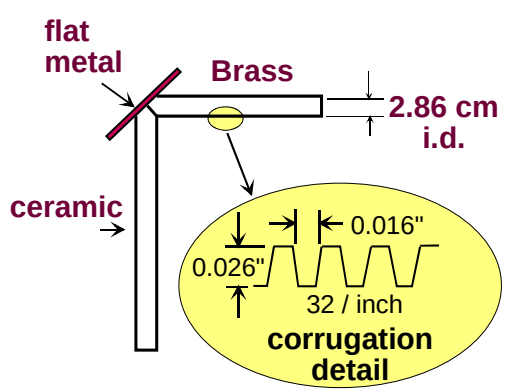


Figure 2. MMW waveguide used for many measurements was a composite of room temperature corrugated brass and high temperature ceramic sections.

Waveguide design:

Demonstrating efficient millimeter-wave waveguides that could be used at temperatures over 1000°C inside the melter and in the melt pool itself was a major accomplishment. It was found that efficient hollow millimeter-wave waveguides could be fabricated from almost any refractory material such as those used to fabricate melter crucibles. The key to this accomplishment is to make the waveguide diameter much larger that the wavelength and use the HE_{11} waveguide mode (transverse magnetic and electric fields) for propagation [3]. The HE_{11} mode is a natural mode inside smooth walled dielectric tubes (the same mode is used inside single mode fiber optic cables at light wavelengths) and can be achieved inside electrically conducting metallic tubes by circumferentially corrugating the inside wall with ¼ λ deep grooves at more than 2.5 grooves per λ of waveguide length. The HE_{11} mode is also ideally suited for monitoring because it launches as a free space Gaussian beam, which is optimum for achieving the smallest possible diffraction limited spot sizes for good spatial resolution.

The waveguide configuration developed for the millimeter-wave sensor

measurements is shown in Figure 2. Unlike earlier work with graphite [4], this one could be used in an oxidizing environment. It consists of a room temperature corrugated waveguide section and a ceramic section, which for most measurements was a mullite ($3Al_2O_3 \cdot 2SiO_2$) tube 1 1/8 inch (28.6 mm) in internal diameter. The MMW receiver frequency used in the tests was 137 GHz (λ=2.19 mm) and the corrugation dimensions shown for the brass section are optimum for that frequency. Theoretically, transmission losses in the corrugated brass waveguide are very small and it can be made as long as necessary to transmit the millimeter-wave signal outside the biological shield of a nuclear waste glass melter (10's of meters). The mullite waveguide was measured to have a loss of about 20% per 0.5 meter. Therefore, it is only used where necessary to access the high temperature environment. Tests were carried out at temperatures of up to 1500°C and with waveguide glass immersions for up to one week in nuclear waste glass melts. Good millimeter-wave performance results were achieved. Some penciling of the immersed waveguide was observed, but did not affect the millimeter-wave performance significantly in the tests so far. Advanced refractories could be used to make the waveguide last as long as the melter crucible. This waveguide technology also has important spin off applications to monitoring in nuclear fusion experiments, nuclear power plants, fossil fuel power plants, and refining manufacturing were diagnostic access to high temperature environments is extremely challenging [5]. ***We used a short grooved aluminum waveguide for our demonstration (as shown in Figures 4 and 5).***

MMW optics:

At high millimeter-wave frequencies optics are the most efficient way of achieving beam splitting and redirection of signal, but millimeter-wave optics are large and very sensitive to alignment. In an industrial scale nuclear waste melter environment, it is not desirable to have sensitive optics that take up a lot of space. Therefore, one of our achievements has been to invent a quasi-optical corrugated waveguide and beamsplitter device that achieves the thermal return reflection function shown in Figure 1 in a compact, rugged component. A cross-section of this device is shown in Figure 3. Crossed corrugated waveguides are machined in an aluminum block with a diagonal spilt as shown to accept a beam splitter. In the experiments carried out so far at 137 GHz the waveguide block was only 2.5 inches (6.4 cm) square by 1.5 inches (3.8 cm) deep with a quartz beamsplitter. The millimeter-wave signal from the melt and receiver field-of-view transverses the block in one direction and the split signal is directed in an orthogonal direction to a TRR mirror (not shown). Insertion losses were measured to be only 0.5%. ***We used this component and a couple of mirrors to get the MMW signal from the grill/bushing to the electronics, as shown in Figures 4 and 5.***

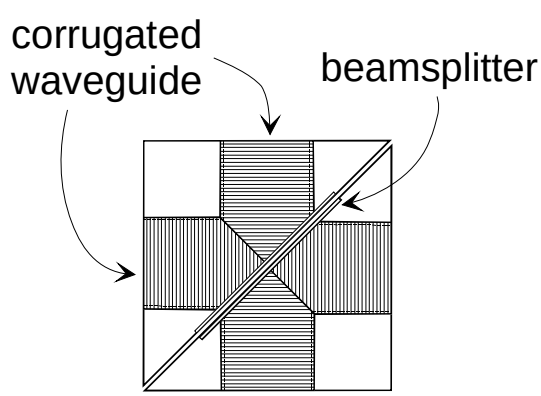


Figure 3. Quasi-optical beamsplitter.

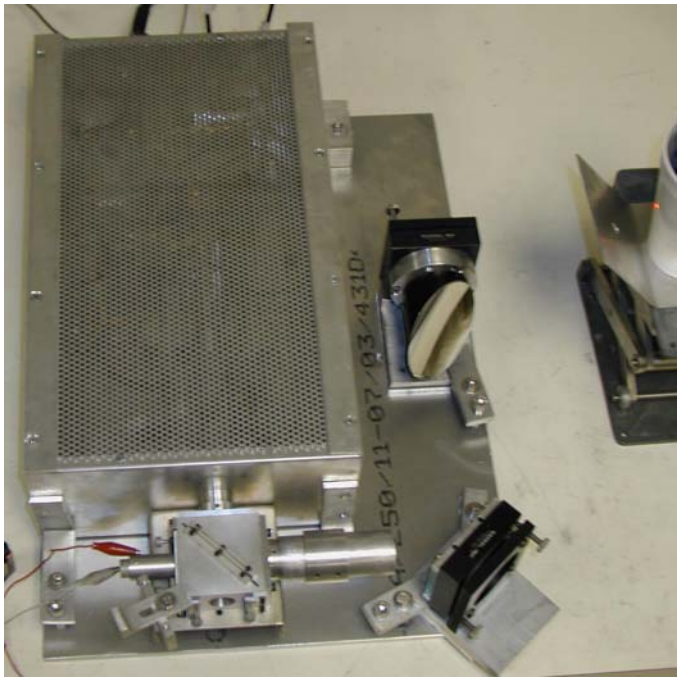


Figure 4. View of MMW pyrometer from front top.
Aluminum plate is 15″ x 21″ x ¼″. Alignment laser collinear with MMW beam passes through 3/8″ diameter aperture in metal fin on jack at approximate location of grill.

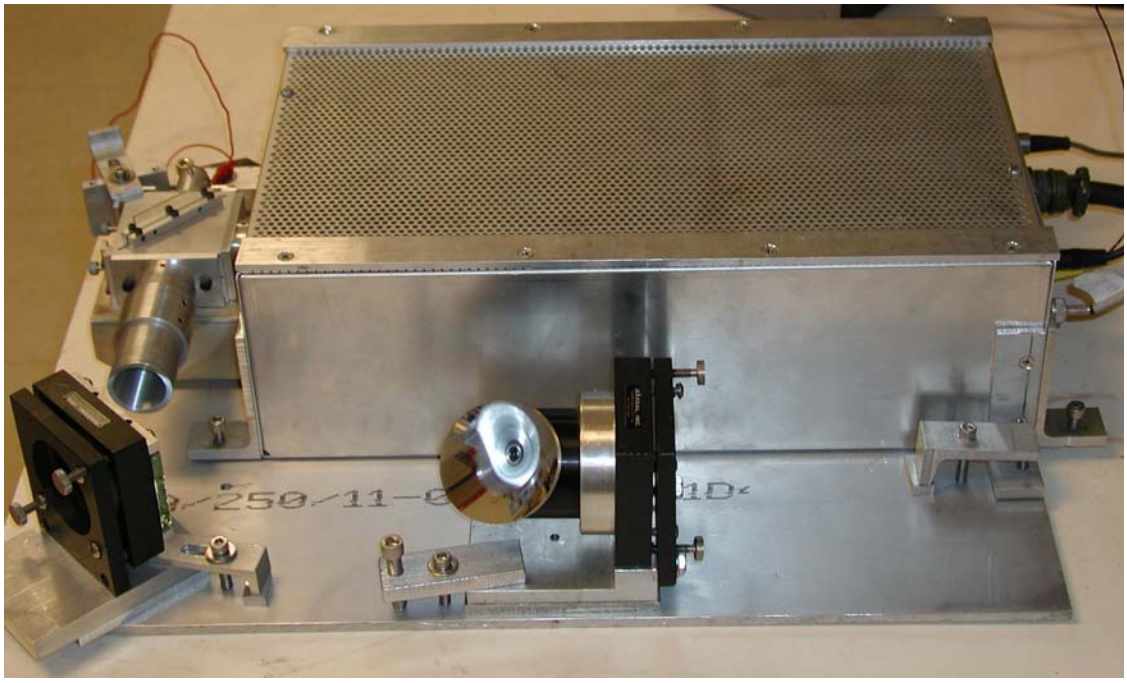


Figure 5. MMW pyrometer system viewed from the grill
The aluminum electronics box with cover is approximately 5.25″high.

Figures 6-8 show different views of the fiber-drawing tower with MMW equipments set up and ready for the demonstration. Figures 9 and 10 show the electronics and other peripheral devices including the laptop showing the run in progress. The waveguide views up the grill at 45° to the horizontal. By moving the stage on which the MMW electronics is mounted along the horizontal axis, we recorded the temperature profile of the grill.

Figure 6. A view of top of the tower

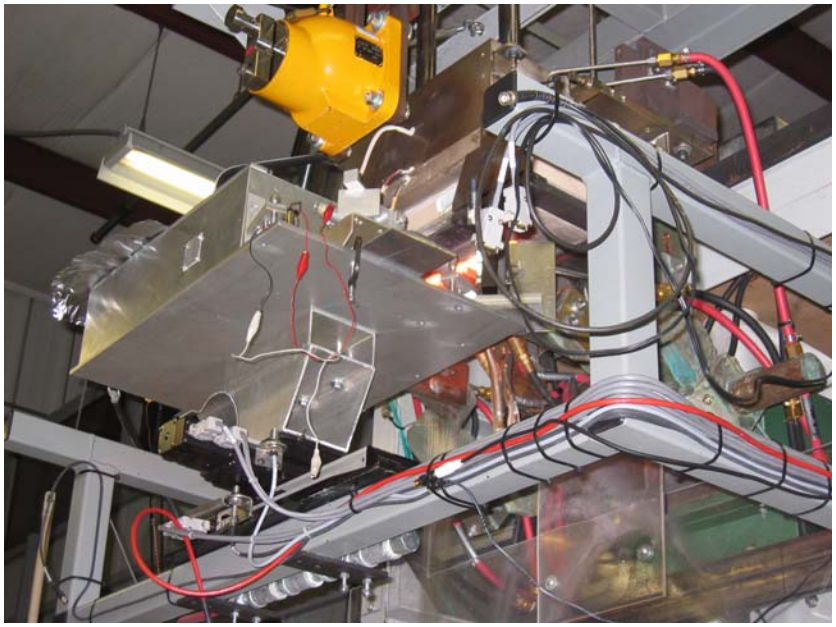


Figure 7. A closer view of the top of the tower (near MMW electronics box)

Figure 8. Full view of the tower

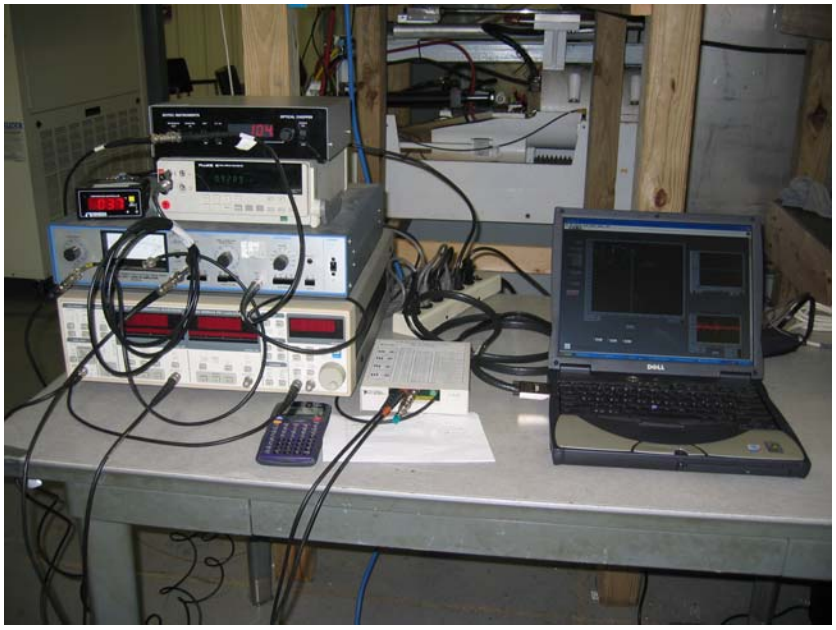


Figure 9. A view of the electronics and laptop

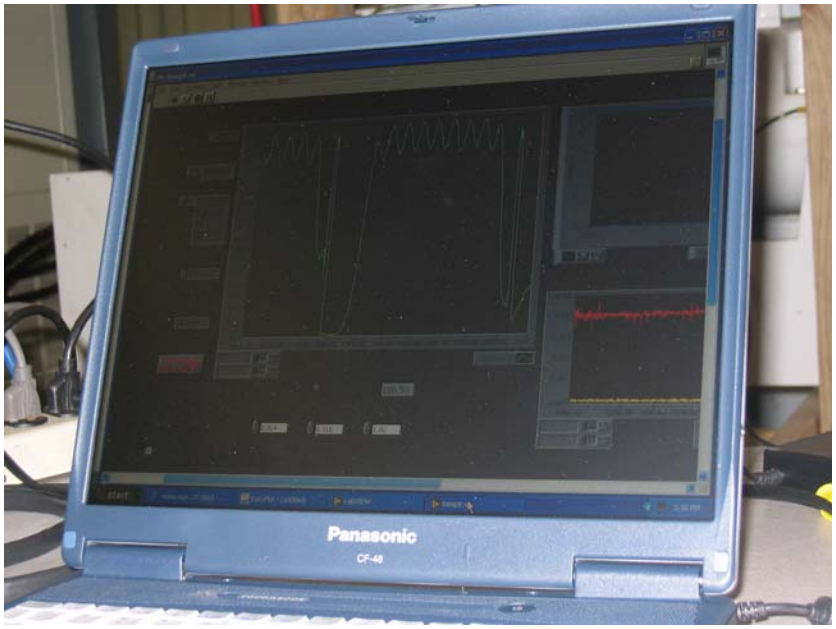


Figure 10. A closer view of the monitor of the laptop showing the real-time data collection

Figures 11 shows typical temperature profiles we got at various locations of the grill. The pofiles distinctly show the oscillating temperature as we scanned from one row of tip to the next. Figure 12 shows the composite of four profiles (shown in Figure 11) for comparison. The green trace corresponded to the front of the grill (viewing from the front of the tower). The black trace corresponded to the middle, and the red and blue, the back of the grill. Though the profiles look similar at the middle of the grill, the edges of the grill show difference. The front and middle profiles are similar to each other except sharper temperature change at the right most side of the grill. The back of the grill show sharp decrease at the edges. These data indicate a non-uniform temperature distribution across the grill. This valuable data could be used to adjust the heaters and other conditions to get a uniform temperature to ensure consistent fiber quality.

Figure 13 shows the MMW temperature profiles corresponding two different grill control thermocouple temperatures. The profiles are very similar.

Additional pictures and all engineering drawings are shown in the Appendix at the end of this report.

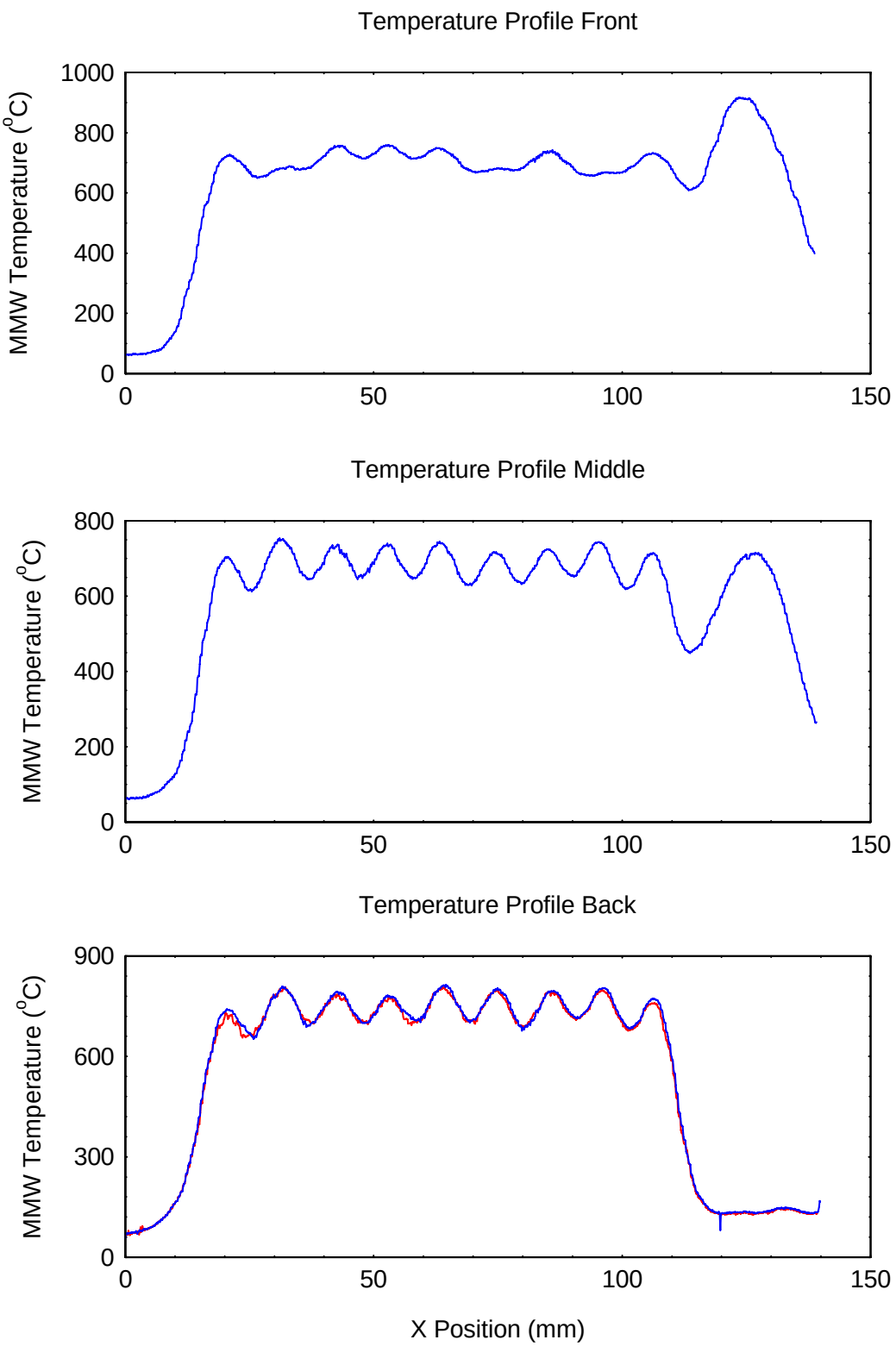


Figure 11. Typical MMW temperature profiles (top = front, middle =middle, and bottom = back of grill viewing from the front of the tower)

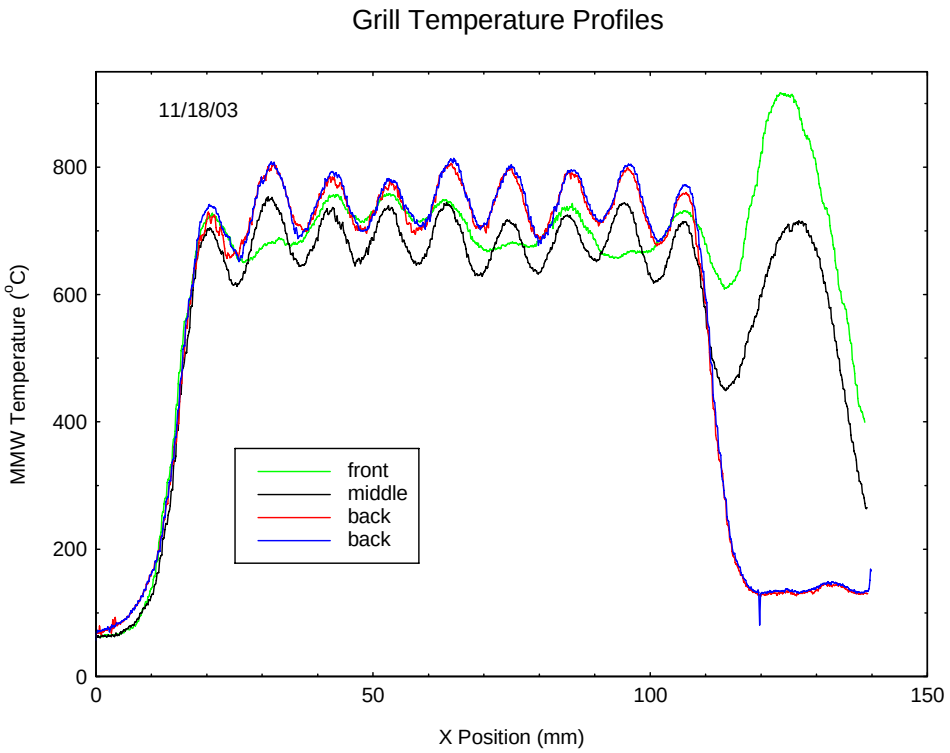


Figure 12. MMW temperature profiles across the grill (from Figure 11)

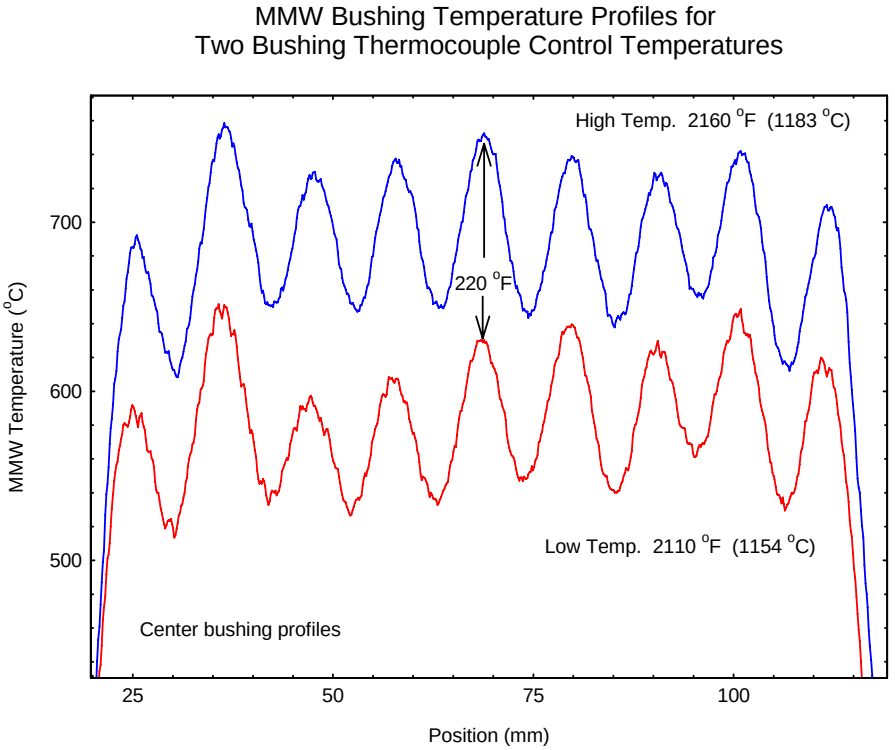


Figure 13. MMW temperature profiles for two different control thermocouple temperatures

Figure 14 shows a record of an entire sequence of a fiber drawing cycle. The scan was done along the middle of the grill. The red trace corresponded to the MMW temperature profile with no winding and the blue trace corresponded to the profile with winding on. At the point of fiber breakage (visually noticed later), the profile changes sharply and dramatically as the busing starts cooling down. After restarting the winding, the profiles change back more or less original profile expected. This is due to bushing warming up once the winding started. This data clearly demonstrates how the MMW technology can track fiber breakage in real time in a plant.

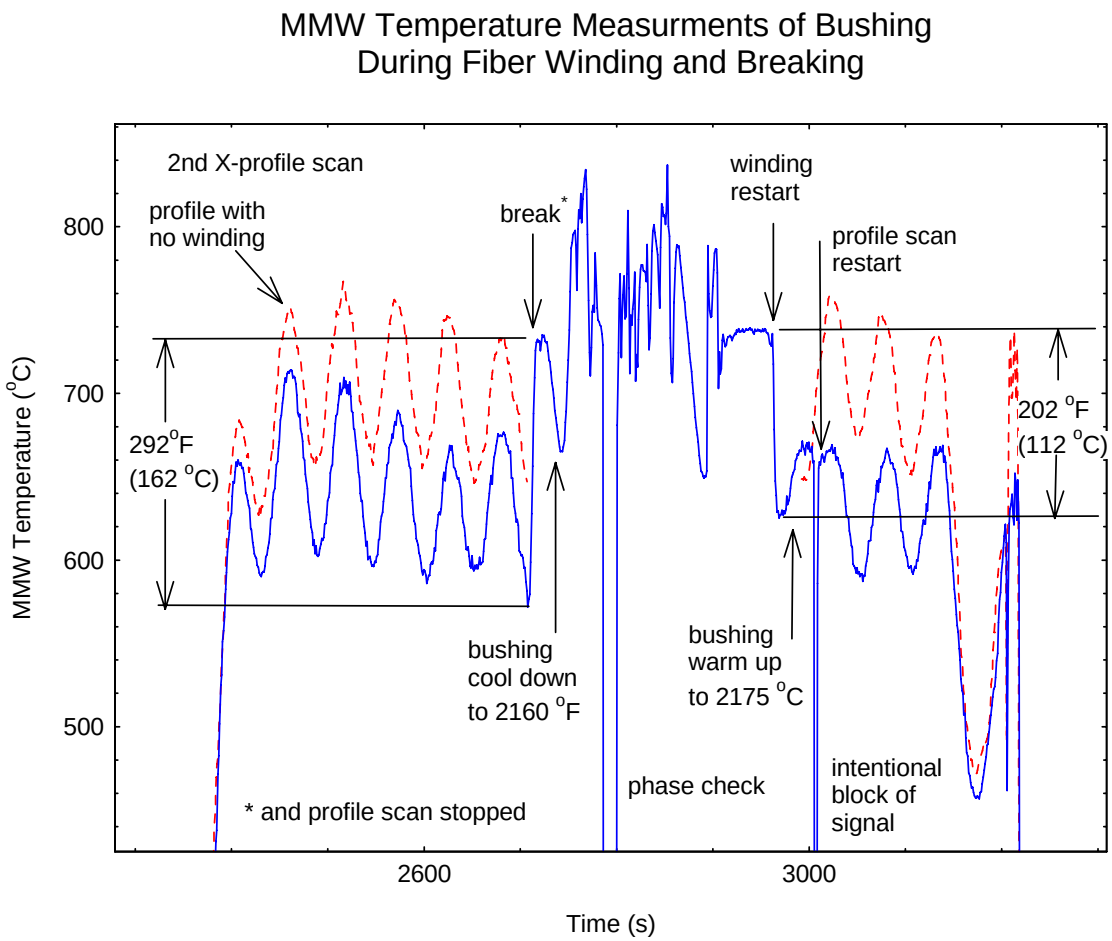


Figure 14. MMW temperature profile and a record of a fiber breaking event

Acknowledgement:

The team is thankful for the support from GMIC for this project. We would also like to record our appreciation to DOE's EMSP for support. We used some of the MMW components that were supported by the EMSP project on MMW diagnostics for nuclear waste vitrification. SK sundaram acknowledges Mr. Mike Elliott for peer-reviewing. PNNL is a multiprogram national laboratory operated by Battelle Memorial Institute for the United States Department of Energy under DE-AC06-76RLO 1830.

References:

1. P. P. Woskov, S. K. Sundaram, G. Daniel, J. S. Machuzak, P. Thomas, "Millimeter-Wave Monitoring of Nuclear Waste Glass Melts – An Overview", Environmental Issues and Waste Management Technologies VII, (Ceramic Transactions, Volume 132) pp. 189-201, 2002 (best paper award American Ceramic Society).
2. P. Woskov, K. Hadidi, S. K. Sundaram, and W. E. Daniel, Jr., "Millimeter-Wave Radiometer Measurement of Emissivity and Temperature by Thermal Return Reflection," International Conference on Infrared and Millimeter-Waves, IEEE 02EX561, 2l1-2l2, San Diego, Sept. 22-26, 2002.
3. J. L. Doane, "Propagation and Mode Coupling in Corrugated and Smooth-Walled Circular Waveguides", Infrared and Millimeter Waves, Vol. 13, K. J. Button Ed., Acadamic Press, New York, Chap. 5, 1985.
4. P. P. Woskov and C. H. Titus, "Graphite Millimeter-Wave Waveguide and Mirror for High Temperature Environments", IEEE Transactions on Microwave Theory and Techniques, vol. 43, 2684-2688, 1995.
5. P. P. Woskov, J. Machuzak, P. Thomas, S. K, Sundaram, and G. Daniel, "High temperature refractory material waveguides for millimeter-wave diagnostics", Proceedings 10th Intern. Symp. On Laser Aided Plasma Diagnostics, 6 pages, Fukuoka, Japan, , Sept. 24-28, 2001.

Appendix: Additional Pictures and Engineering Drawings

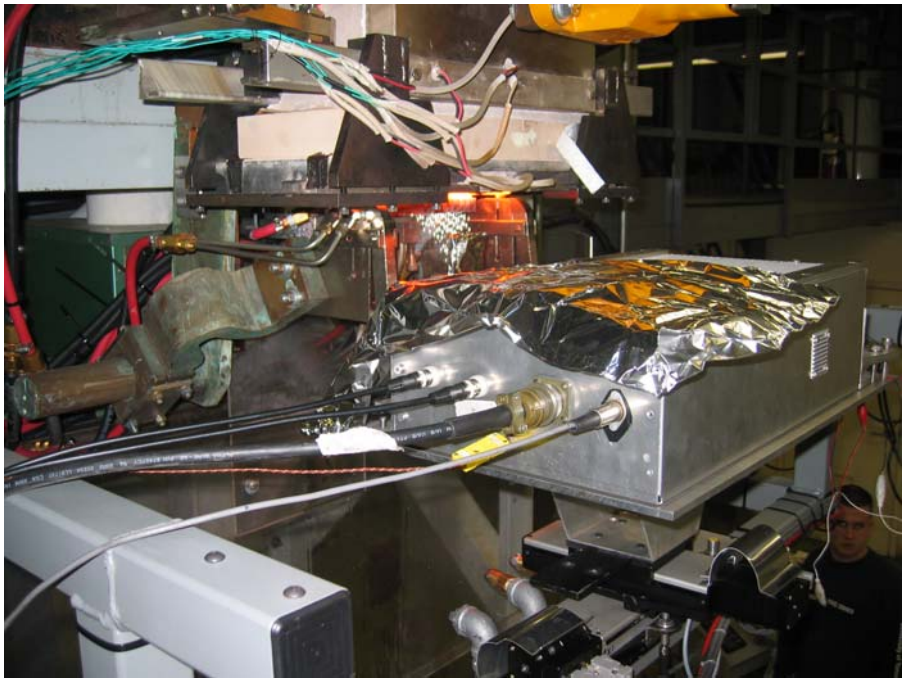


Figure A1. Close view of MMW electronics box close to the hot bushing

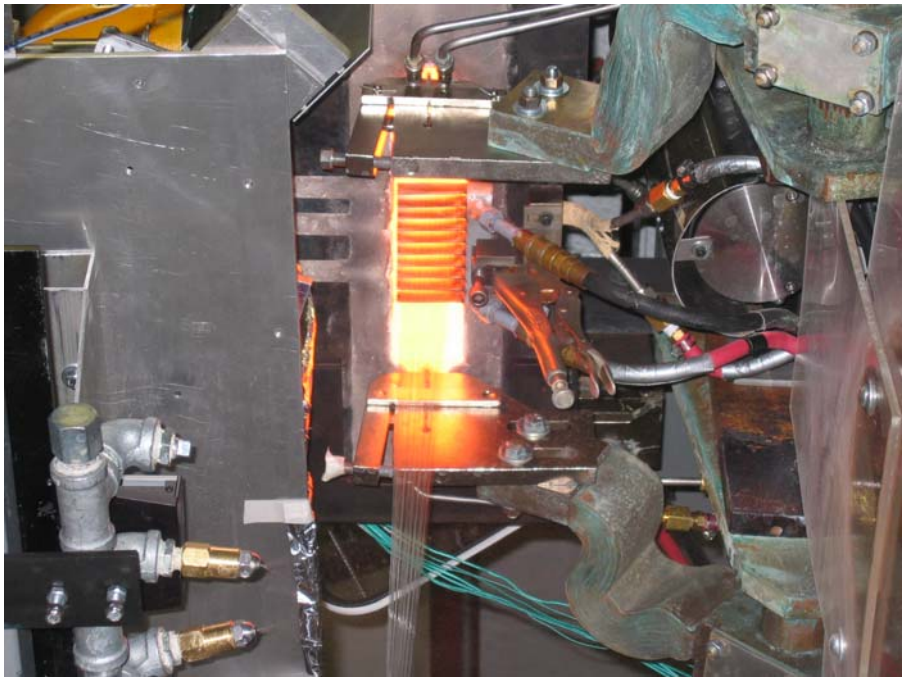


Figure A2. View of the hot grill from the bottom of the tower

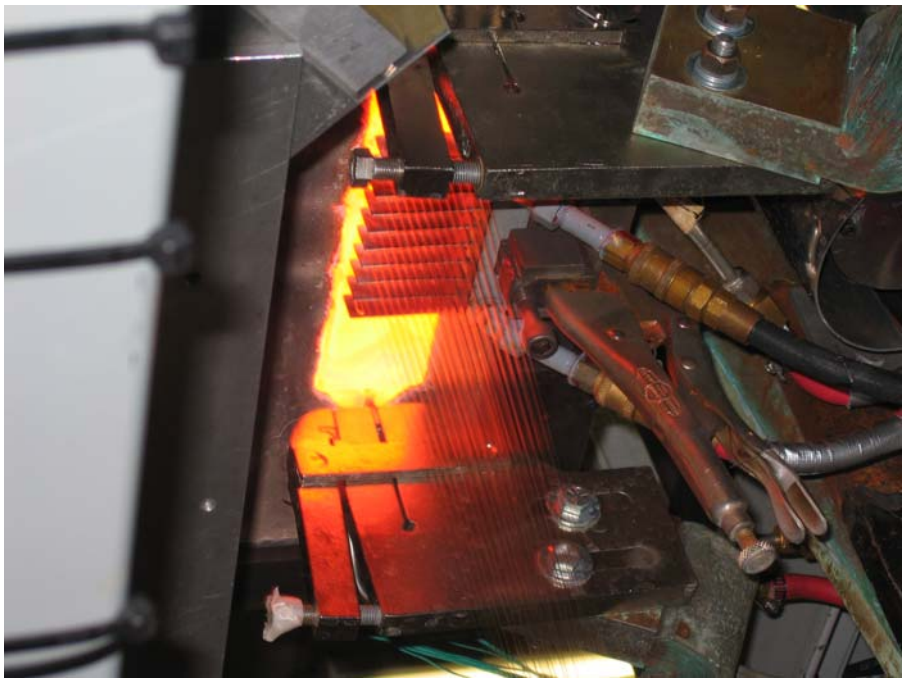


Figure A3. Closer view of the hot grill from the bottom of the tower

Figure A4. Top view of E-glass marbles

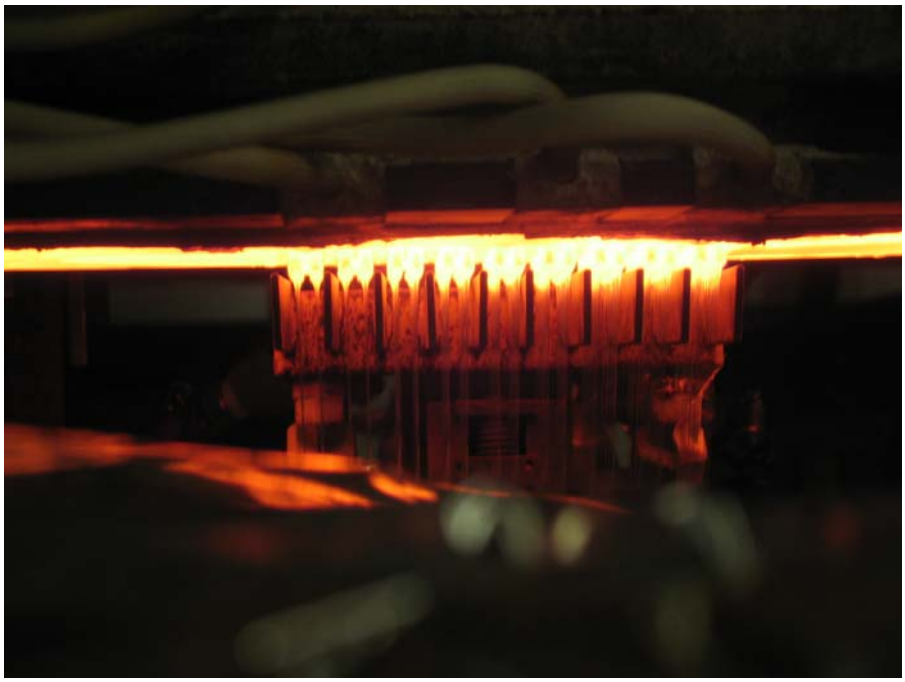


Figure A5. Close view of the hot bushing

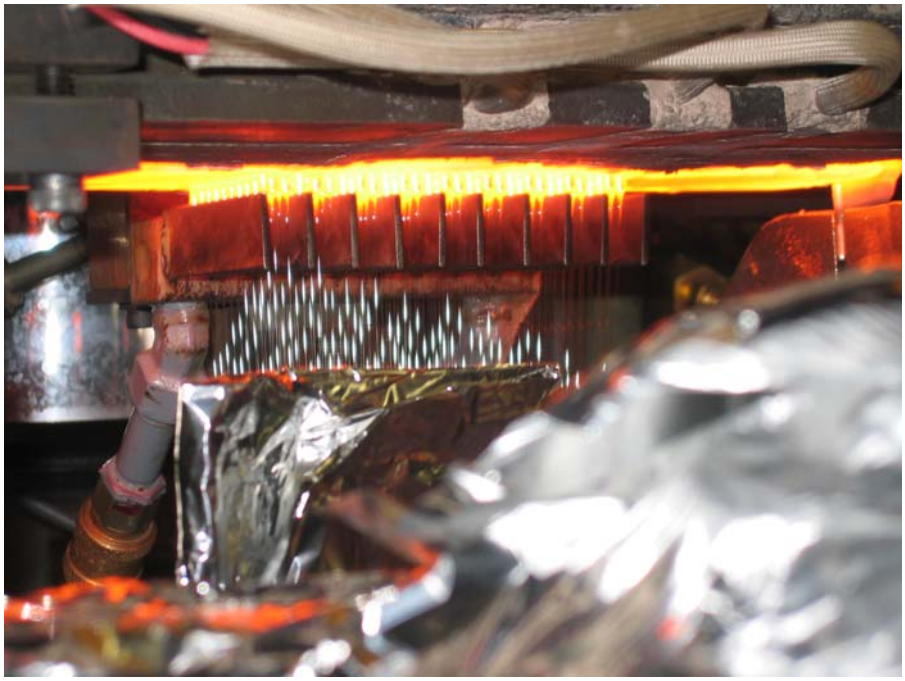


Figure A6. Close view of the hot bushing and fiber drawing

Figures A7. Drs. Woskov and Sanger discussing the data

Figures A7. Drs. Sundaram and Sanger looking at the data

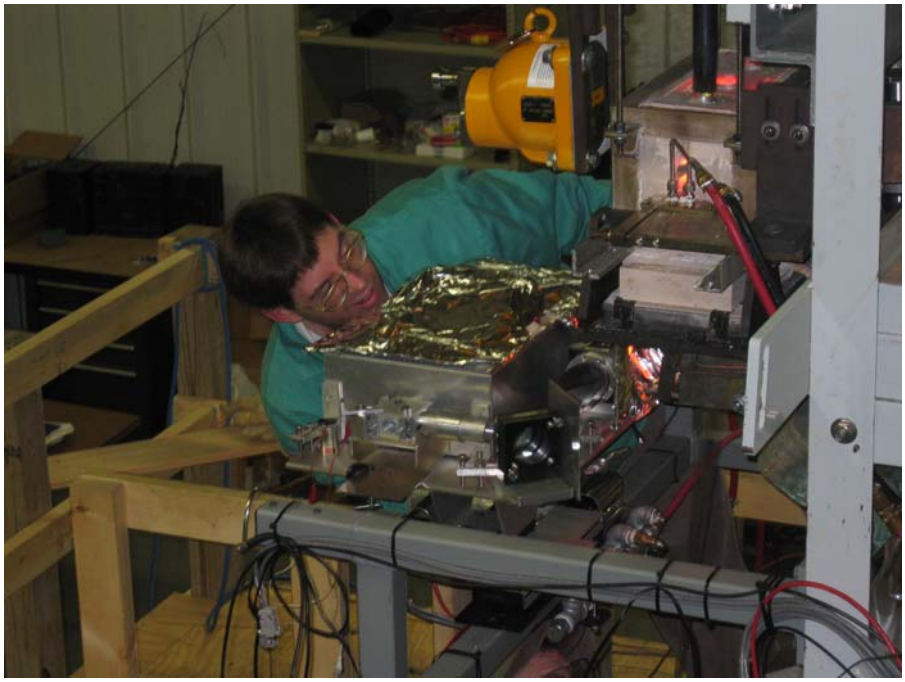
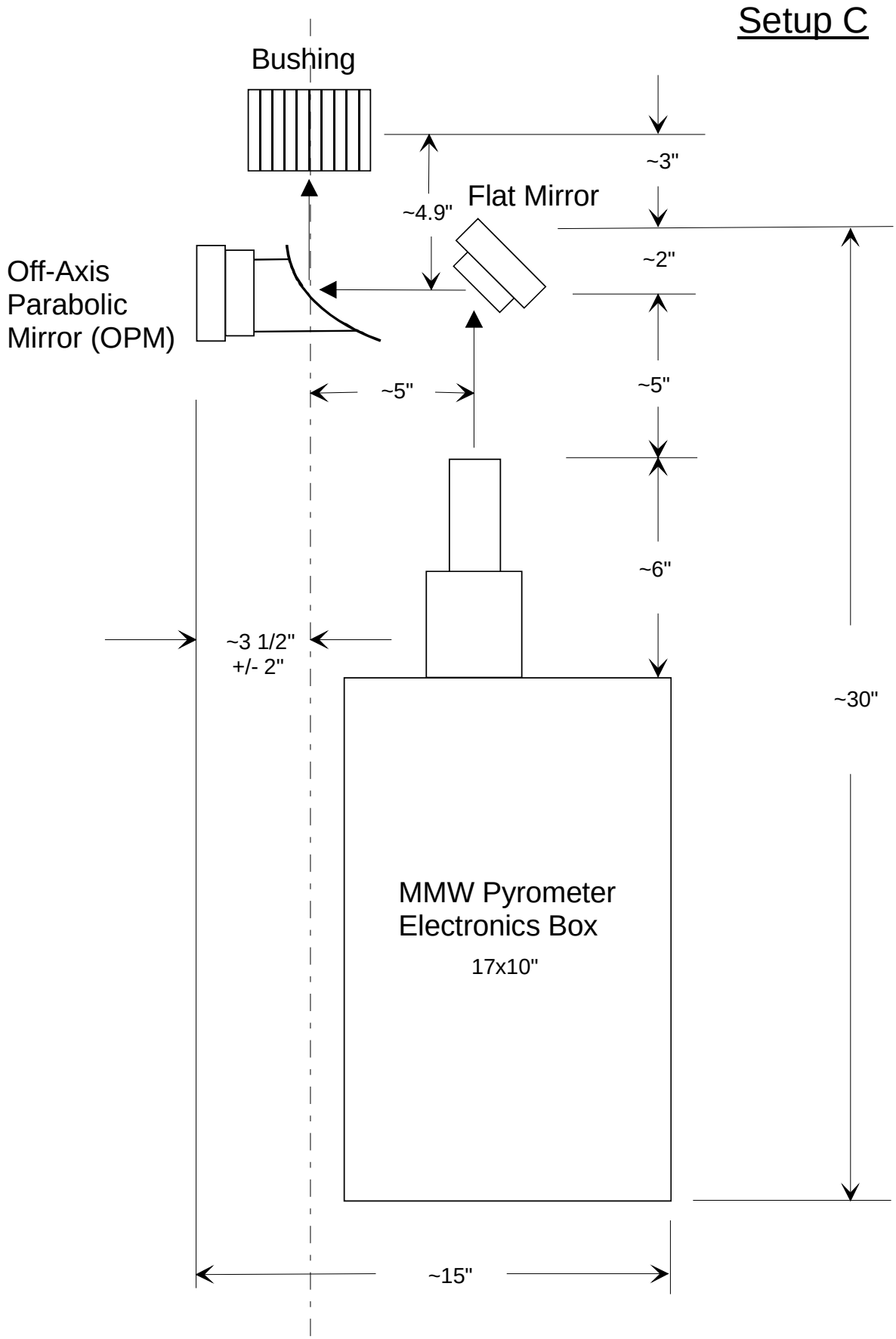
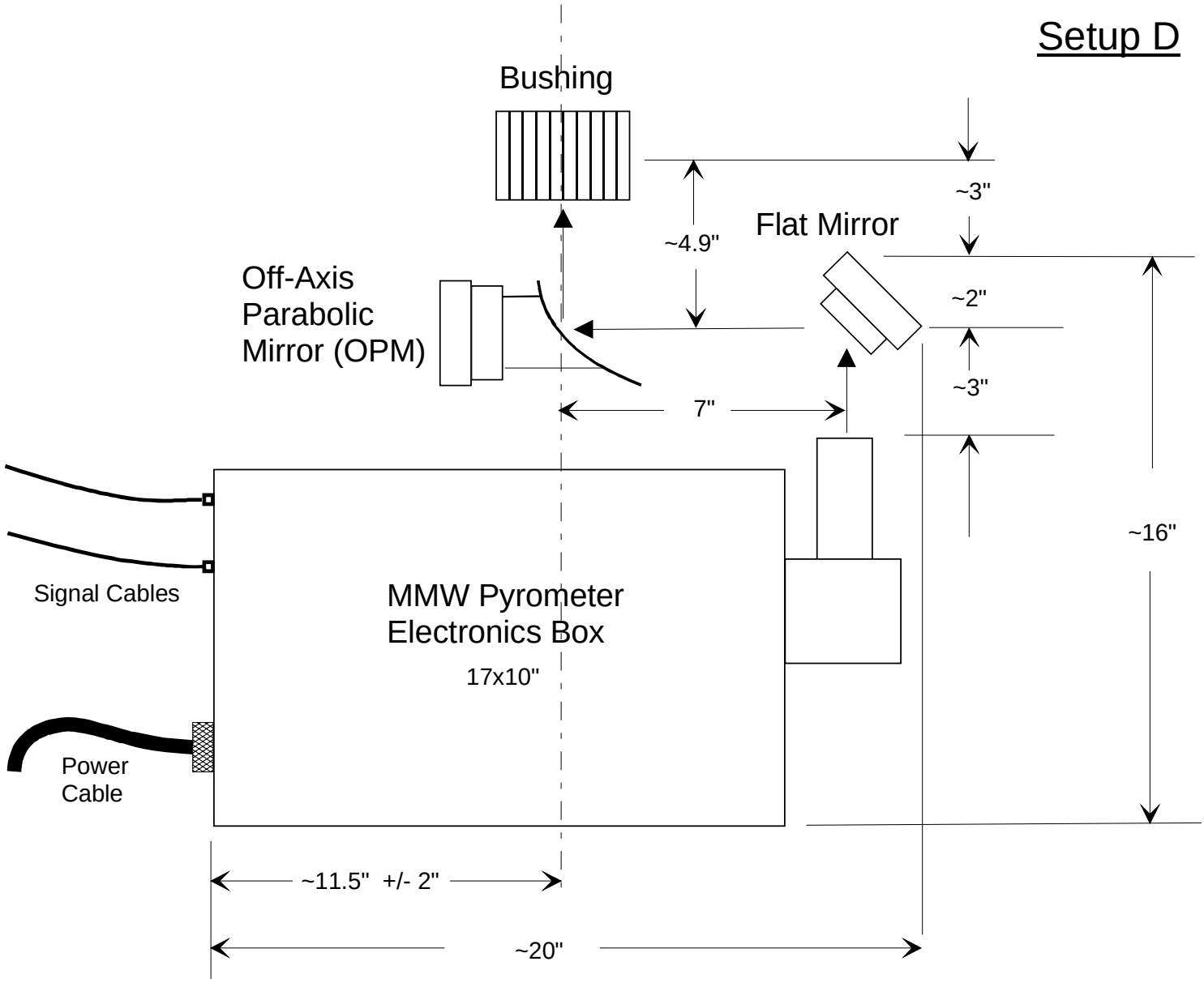


Figure A9. Dr. Leonard examining the alignments


Setup C
Bushing
~3"
Flat Mirror
~4.9"
~2"
Off-Axis
Parabolic
Mirror (OPM)
~5"
~5"
~6"
~3 1/2"
+/- 2"
~30"
MMW Pyrometer
Electronics Box
17x10"
~15"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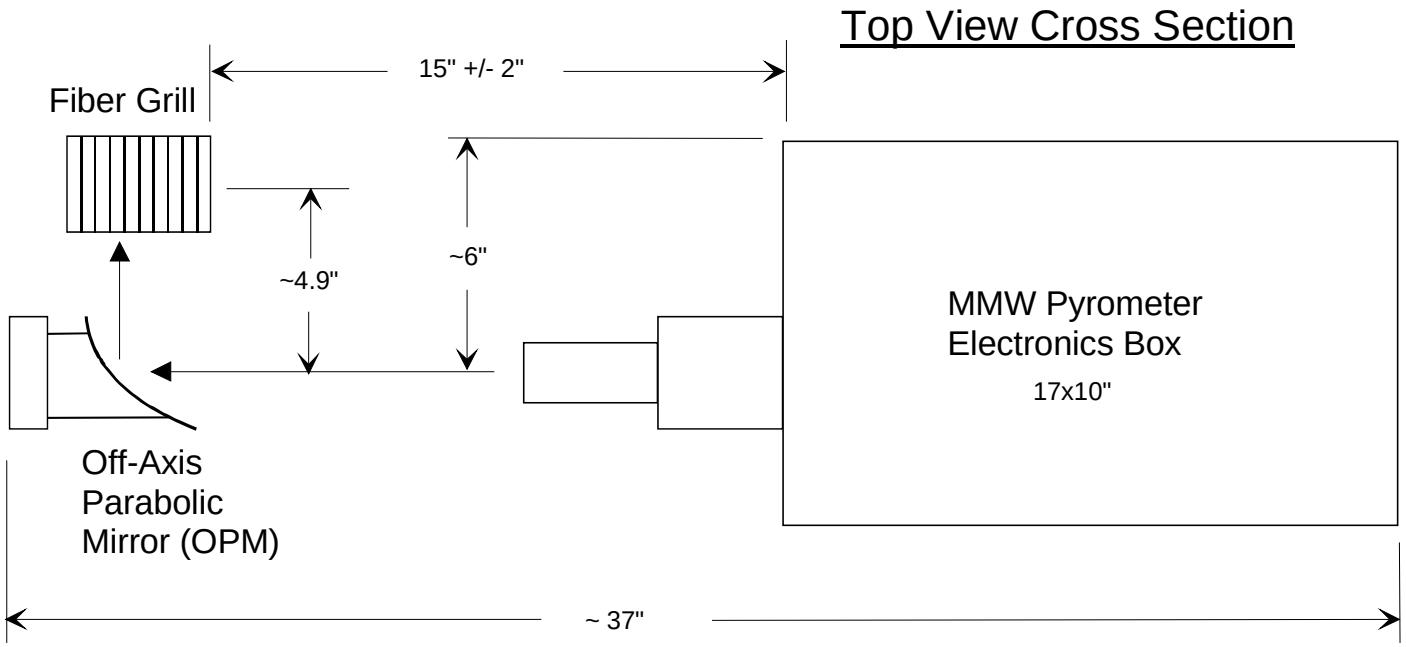
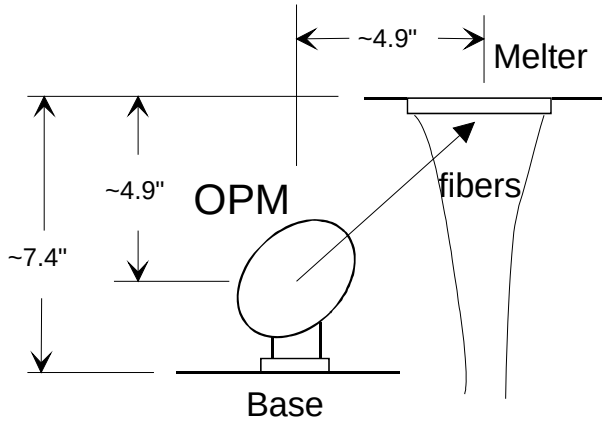
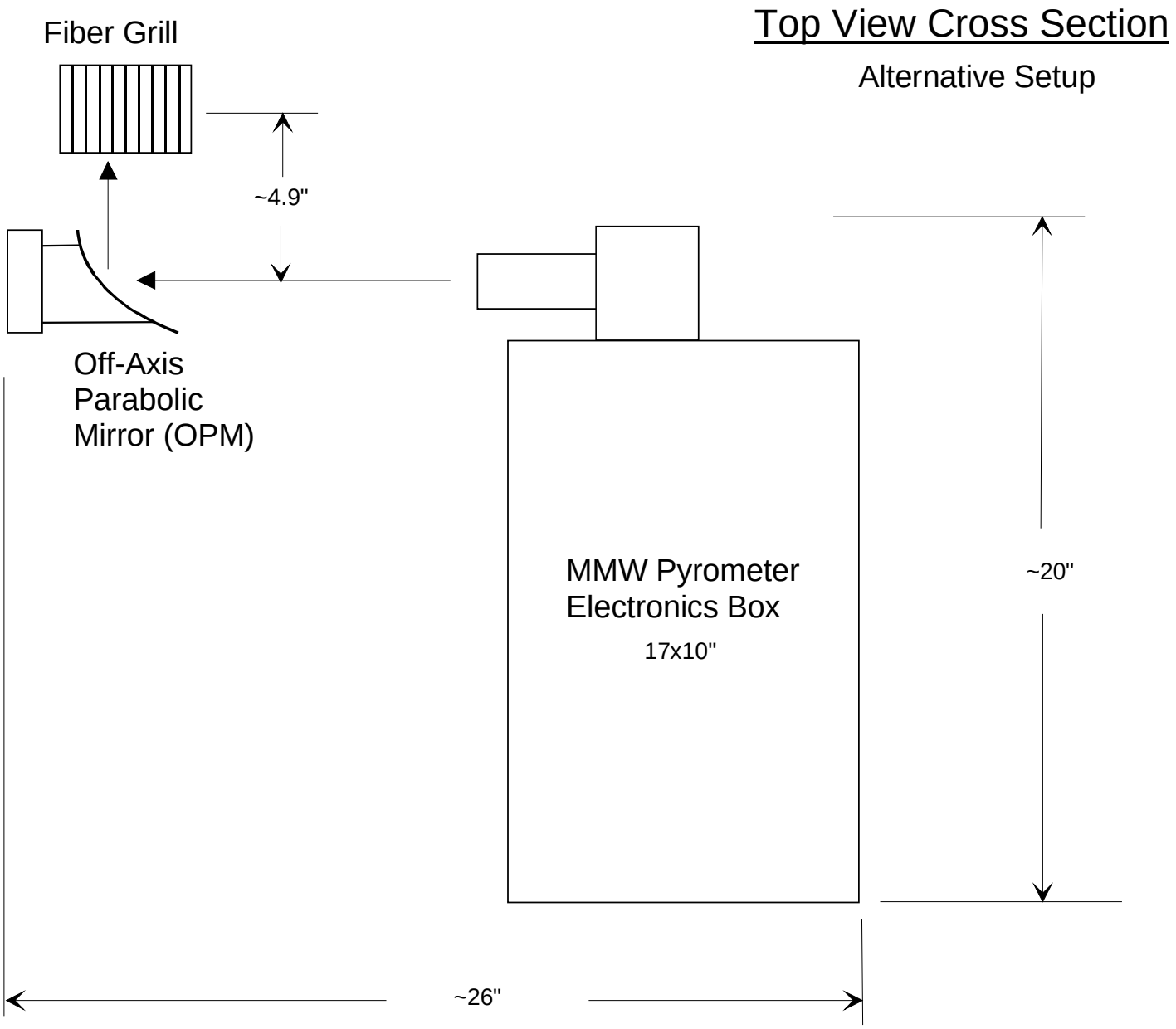
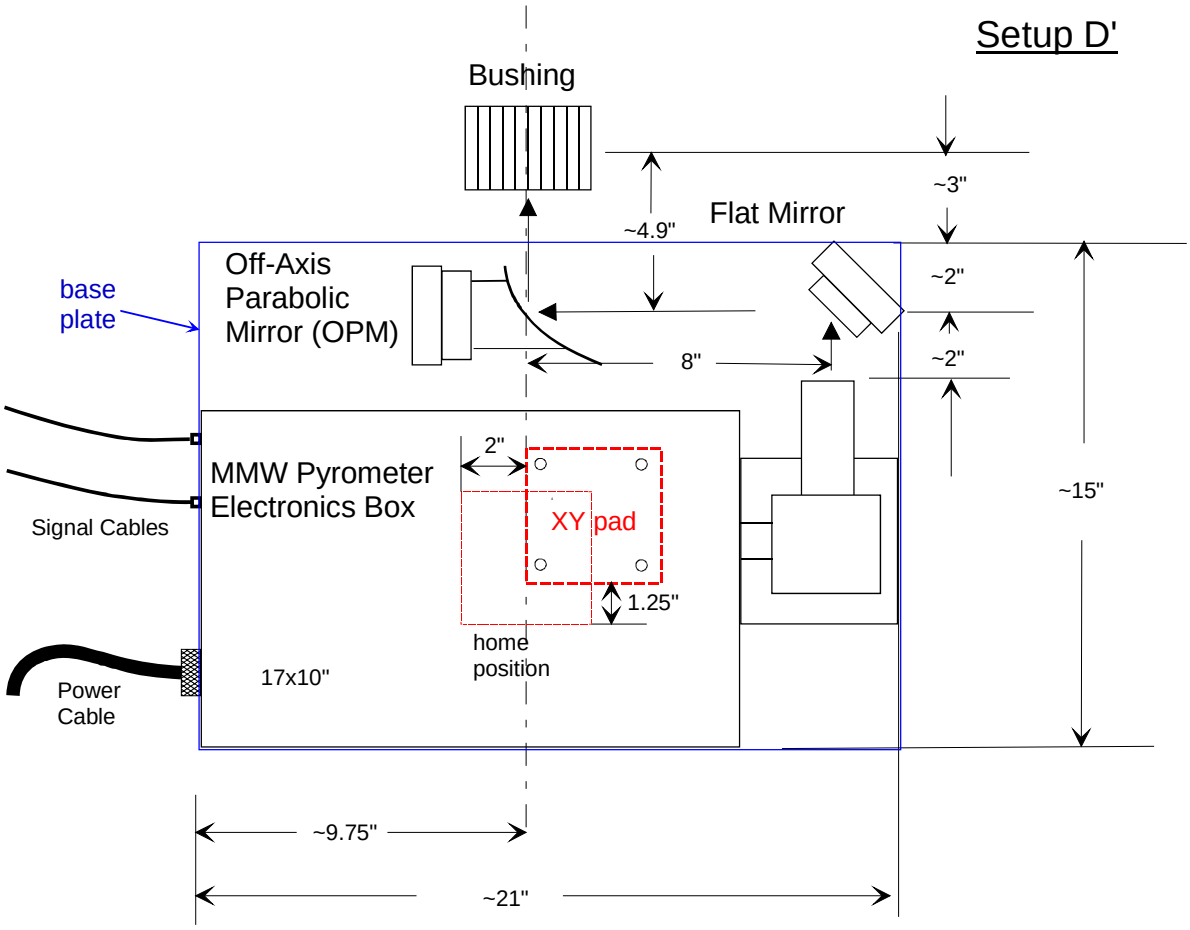
Signal Cables
MMW Pyrometer
Electronics Box
17x10"
Power
Cable
~11.5" +/- 2"
~20"





Elevation View


Top View Cross Section
Alternative Setup
Fiber Grill
~4.9"
Off-Axis
Parabolic
Mirror (OPM)
MMW Pyrometer
Electronics Box
17x10"
~20"
~26"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MMW Pyrometer
Electronics Box
XY pad
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Signal Cables
1.25"
home
position
17x10"
Power
Cable
~9.75"
~21"